

# Nonstandard interactions jeopardizing the hierarchy sensitivity of DUNE

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In this work we consider the effect of non-standard interactions (NSI) on the propagation of neutrinos through matter and how it affects the hierarchy sensitivity of the DUNE experiment. We emphasize on the special case when the diagonal NSI parameter  $\epsilon_{ee} = -1$  and nullifies the standard matter effect. We show that, if in addition, there is maximal CP violation then this gives rise to an exact intrinsic hierarchy degeneracy, in the appearance channel, irrespective of the baseline and energy. Introduction of off-diagonal NSI parameter,  $\epsilon_{e\tau}$ , shifts the position of intrinsic degeneracy to a different  $\epsilon_{ee}$ . Moreover the unknown magnitude and phases of the off-diagonal NSI parameters can give additional degeneracies. Overall, given the current model independent limits on NSI parameters, no hierarchy sensitivity can be observed in the DUNE experiment if NSIs exist in nature. A signal of neutrino mass hierarchy at DUNE will therefore be able to rule out certain ranges of the NSI parameters.

PACS numbers: 13.15.+g, 14.60.Pq, 14.60.St

**Introduction:** Phenomenal experiments over the past decades have established neutrino oscillations and led us into an era of precision measurements in the leptonic sector. Current data is able to determine the two mass squared differences ( $\Delta m_{21}^2 = m_2^2 - m_1^2$ ,  $|\Delta m_{31}^2| = |m_3^2 - m_1^2|$ ,  $m_1, m_2, m_3$  being the mass states) and three leptonic mixing angles ( $\theta_{12}, \theta_{23}, \theta_{13}$ ) with considerable precision [1, 2]. Recently, the on-going T2K and NO $\nu$ A experiments have hinted that Dirac CP violating phase is maximal i.e.  $\delta_{CP} = -\pi/2$  [3, 4] although at  $3\sigma$  the full range ( $0 - 2\pi$ ) remains allowed. This leaves determination of neutrino mass hierarchy i.e. whether the mass pattern has normal hierarchy (NH,  $m_3 > m_2 > m_1$ ) or inverted hierarchy (IH,  $m_3 < m_1 \approx m_2$ ), octant of  $\theta_{23}$  i.e. whether the  $\theta_{23} < \pi/4$  and lies in lower octant (LO) or it is  $> \pi/4$  and is in the higher octant (HO), and measurement of  $\delta_{CP}$  as the major objectives of ongoing and future experiments.

Although neutrino oscillation has been established as the dominant phenomenon to explain the results of various experiments, the possibility of sub-leading effects originating from *new physics* beyond the Standard Model (SM) cannot be ignored. Among various beyond three-generation oscillation scenarios, non-standard interactions have received a lot of attention lately. Notably it is shown in [5, 6] that NSI effects can be instrumental in resolving the existing discrepancies in the best-fit values of three neutrino parameters coming from different experiments. Exploration of NSI parameters has got further boost with the emergence of next generation experiments

like DUNE, [7–13], T2HK and T2HKK [14].

In this work we focus on the matter NSI which affects the neutrino propagation. In presence of this the charge current matter potential needs to be extended and can be described by dimension-six four-fermion operators of the form [15]<sup>1</sup>

$$\mathcal{L}_{\text{NSI}}^{\text{NC}} = (\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta) (\bar{f} \gamma_\rho P_C f) 2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fC} + \text{h.c.} \quad (1)$$

where  $\epsilon_{\alpha\beta}^{fC}$  are NSI parameters,  $\alpha, \beta = e, \mu, \tau$ ,  $C = L, R$  denotes the chirality,  $f = u, d, e$ , and  $G_F$  is the Fermi constant. The Hamiltonian in the flavor basis can be written as,

$$H = \frac{1}{2E} [U \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U^\dagger + V], \quad (2)$$

where  $U$  is the PMNS mixing matrix having three mixing angles ( $\theta_{ij}$ ,  $i < j = 1, 2, 3$ ) and a CP phase  $\delta_{CP}$ .  $V$  is the matter potential arising from the interactions of neutrinos through propagation,

$$V = A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}. \quad (3)$$

where,  $A \equiv 2\sqrt{2} G_F N_e E$  and  $\epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \equiv \sum_{f,C} \epsilon_{\alpha\beta}^{fC} \frac{N_f}{N_e}$ , with  $N_f$  the number density of fermion  $f$ . The unit contribution to the (1,1) element of the  $V$  matrix is the usual matter term arising due to the standard charged-current interactions. Here, diagonal elements of the  $V$  matrix are real due to the Hermiticity of the Hamiltonian in eq.(2).

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<sup>1</sup> We neglect the production and detection NSI, bounds on which are stronger by an order of magnitude than matter NSI [16].

Various symmetry transformations render this Hamiltonian invariant [11, 17, 18] and can give rise to parameter degeneracies. In [7, 19]  $\theta_{23}$  and  $\delta_{CP}$  degeneracy between standard and non-standard parameters were studied for DUNE/T2HK assuming hierarchy to be known. Degeneracy between octant of  $\theta_{23}$  and off-diagonal NSI parameters was also explored in [8]. In [10], degeneracies between SM with CP conservation and a model with matter NSI parameters were investigated by considering either diagonal or one or more off-diagonal NSI parameters at a time in the context of T2K, NO $\nu$ A and DUNE experiments. Reference [11] showed the existence of a generalized mass ordering degeneracy and partial recovery of this when DUNE data with no NSI is fitted by allowing simultaneous presence of diagonal ( $\epsilon_{ee}$ ) and one off-diagonal ( $\epsilon_{e\tau}$ ) NSI parameters.

In this work, we study, at a probability level, the hierarchy degeneracy as a function of  $\delta_{CP}$  for the DUNE baseline considering only diagonal NSI parameter ( $\epsilon_{ee}$ ) as well as simultaneous presence of  $\epsilon_{ee}$  and  $\epsilon_{e\tau}$ . For the case with only diagonal NSI parameter, we observe from eq.(3) that for  $\epsilon_{ee} = -1$ , the NSI effect cancels the standard matter effect and the probability for  $\nu_\mu - \nu_e$  transition  $P_{\mu e}$  is just the vacuum oscillation probability which contains  $\Delta_{31} \rightarrow -\Delta_{31}$  and  $\delta_{CP} \rightarrow \pi - \delta_{CP}$  degeneracy. For  $\delta_{CP} = \pm\pi/2$ , this becomes an exact intrinsic hierarchy degeneracy which will be present irrespective of the baseline of the experiment and the neutrino beam energy. Note that this is a special case of the  $\epsilon_{ee} \rightarrow -\epsilon_{ee} - 2$  and  $\delta \rightarrow \pi - \delta$  degeneracy discussed in [11]. We emphasize

on the intrinsic nature of this degeneracy for  $\epsilon_{ee} = -1$  and  $\delta_{CP} = \pm\pi/2$ . For these values the degeneracy cannot be resolved even if both parameters are measured precisely. It is noteworthy that  $\delta_{CP} = -\pi/2$  is the preferred value from the current data and a fit to the SuperKamioKande data assuming NSI gives the best-fit as  $\epsilon_{ee} = -1$ ,  $|\epsilon_{e\tau}| = 0$  [20]. Adding off-diagonal NSI parameters introduces matter dependent hierarchy sensitivity terms in the probability. We consider the effect of the off-diagonal parameter  $\epsilon_{e\tau}$ , as an illustrative example, and show that the inclusion of this shifts the position of the intrinsic degeneracy for  $\delta_{CP} = \pm\pi/2$  to a different value of  $\epsilon_{ee}$ . However, we find that the amount of this shift depends on the energy. Thus the intrinsic degeneracy which was independent of energy becomes energy dependent with the inclusion of  $\epsilon_{e\tau}$ . But due to the presence of the phases in the off-diagonal terms there can be additional degeneracies. As a combination of all these factors the hierarchy sensitivity of long baseline (LBL) experiments can get compromised. Considering the model independent bounds on the NSI parameters, we demonstrate how NSI if present in nature, can affect the mass hierarchy sensitivity of DUNE. We also discuss bounds on NSI parameters that can be obtained should DUNE see a mass hierarchy sensitivity.

**Probability level study:** The relevant appearance channel probability ( $P_{\mu e}$ ) for normal hierarchy (NH), can be expressed in terms of small parameters,  $s_{13}$ ,  $r = \Delta m_{21}^2/\Delta m_{31}^2$  and  $\epsilon_{\alpha\beta}$  except  $\alpha, \beta = e$  as [10],

$$\begin{aligned}
P_{\mu e} = & x^2 f^2 + 2xyfg \cos(\Delta + \delta_{CP}) + y^2 g^2 \\
& + 4\hat{A}\epsilon_{e\mu} \{xf[s_{23}^2 f \cos(\phi_{e\mu} + \delta) + c_{23}^2 g \cos(\Delta + \delta + \phi_{e\mu})] + yg[c_{23}^2 g \cos \phi_{e\mu} + s_{23}^2 f \cos(\Delta - \phi_{e\mu})]\} \\
& + 4\hat{A}\epsilon_{e\tau} s_{23} c_{23} \{xf[f \cos(\phi_{e\tau} + \delta) - g \cos(\Delta + \delta + \phi_{e\tau})] - yg[g \cos \phi_{e\tau} - f \cos(\Delta - \phi_{e\tau})]\} \\
& + 4\hat{A}^2 g^2 c_{23}^2 |c_{23}\epsilon_{e\mu} - s_{23}\epsilon_{e\tau}|^2 + 4\hat{A}^2 f^2 s_{23}^2 |s_{23}\epsilon_{e\mu} + c_{23}\epsilon_{e\tau}|^2 \\
& + 8\hat{A}^2 fg s_{23} c_{23} \{c_{23} \cos \Delta [s_{23}(\epsilon_{e\mu}^2 - \epsilon_{e\tau}^2) + 2c_{23}\epsilon_{e\mu}\epsilon_{e\tau} \cos(\phi_{e\mu} - \phi_{e\tau})] - \epsilon_{e\mu}\epsilon_{e\tau} \cos(\Delta - \phi_{e\mu} + \phi_{e\tau})\} \\
& + \mathcal{O}(s_{13}^2 \epsilon, s_{13} \epsilon^2, \epsilon^3),
\end{aligned} \tag{4}$$

where

$$\begin{aligned}
x = 2s_{13}s_{23}, \quad y = rc_{23} \sin 2\theta_{12}, \quad (s_{ij} = \sin \theta_{ij}, c_{ij} = \cos \theta_{ij}, i < j, i, j = 1, 2, 3) \\
\Delta = \frac{\Delta m_{31}^2 L}{4E}, \quad \hat{A} = \frac{A}{\Delta m_{31}^2}, \quad f, \bar{f} = \frac{\sin[\Delta(1 \mp \hat{A}(1 + \epsilon_{ee}))]}{(1 \mp \hat{A}(1 + \epsilon_{ee}))}, \quad g = \frac{\sin[\hat{A}(1 + \epsilon_{ee})\Delta]}{\hat{A}(1 + \epsilon_{ee})}
\end{aligned} \tag{5}$$

The expressions for the inverted hierarchy (IH) can be obtained by replacing  $\Delta m_{31}^2 \rightarrow -\Delta m_{31}^2$  (implying  $\Delta \rightarrow -\Delta$ ,  $\hat{A} \rightarrow -\hat{A}$  (i.e.  $f \rightarrow -\bar{f}$  and  $g \rightarrow -g$ ),  $y \rightarrow -y$ ). Similar expressions for anti neutrino probability ( $P_{\bar{\mu}e}$ ) can be obtained by replacing  $\hat{A} \rightarrow -\hat{A}$  (i.e.  $f \rightarrow \bar{f}$ ),  $\delta_{CP} \rightarrow -\delta_{CP}$ . We note from the above that the only

diagonal parameter to which appearance channel is sensitive is  $\epsilon_{ee}$ . Also note that since the appearance channel probability contains terms of the form  $\sin 2\theta_{12}$  the  $s_{12} \leftrightarrow c_{12}$  transformation is not very important in our discussion and we concentrate on the region  $\theta_{12} < \pi/4$ . In the absence of off-diagonal NSI parameters, the probability expression is just the first line of eq.(4). The NSI

contribution appears only in  $f$ ,  $\bar{f}$  and  $g$  terms via  $\epsilon_{ee}$  which is not treated as a small parameter in this formulation. The behavior of  $P_{\mu e}$  as a function of  $\epsilon_{ee}$  is shown in fig. (1) for a fixed energy  $E = 2$  GeV and  $\delta_{CP} = -90^\circ$ . The top (bottom) panel is for neutrino (antineutrino). Depending on whether the hierarchy is NH or IH and octant is LO or HO we have 4 possible combinations of hierarchy - octant that correspond to 4 different bands that are labeled in the figure.

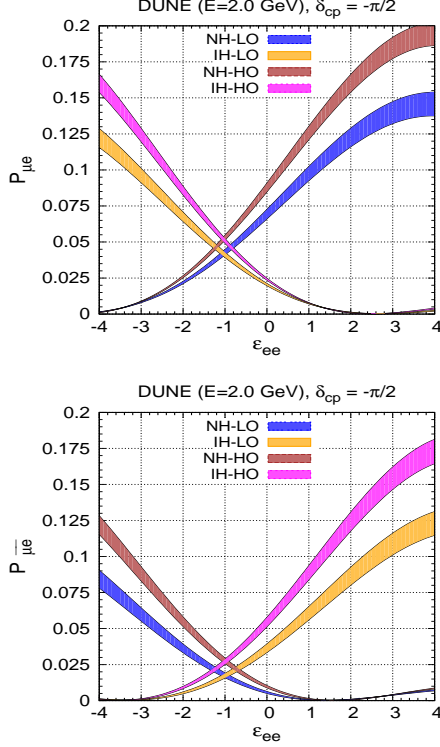


FIG. 1: Top (bottom) panel represents  $P_{\mu e}$  ( $P_{\mu \bar{e}}$ ) vs  $\epsilon_{ee}$  for DUNE by considering fixed energy ( $E=2$  GeV) and  $\delta_{CP} = -90^\circ$ . Here the bands are over  $\theta_{23}$ , for LO ( $\theta_{23} = 39^\circ - 42^\circ$ ) and for HO ( $\theta_{23} = 48^\circ - 51^\circ$ ). Also blue and brown (magenta and yellow) corresponds to NH (IH).

The width of the bands are due to variation over  $\theta_{23}$  in the particular octant. We observe from the top panel that the probability is a rising (falling) function of  $\epsilon_{ee}$  when neutrino mass pattern follow NH (IH) for both the octant. This scenario gets reversed in case of antineutrinos as we can see from bottom panel of fig. (1). The value  $\epsilon_{ee} = 0$ , represents standard oscillation case in presence of matter i.e. without NSI. As DUNE has large matter effect, one can see from top panel that there is a huge separation between NH and IH bands for this value for neutrinos. For antineutrinos this separation is relatively less because the latter have less matter effect. But in presence of NSI, DUNE loses hierarchy sensitivity due to additional degeneracy creeping in through the NSI parameters. From fig. (1) we observe that ( $\epsilon_{ee} = 0$ , NH) is degenerate with ( $\epsilon_{ee} = -2$ , IH) for both the octants in the case of neutrinos as well as antineutrinos. Similar degeneracies can be observed for ( $\epsilon_{ee} = 1$ , NH) with

( $\epsilon_{ee} = -3$ , IH) and ( $\epsilon_{ee} = 2$ , NH) with ( $\epsilon_{ee} = -4$ , IH) in the presence of NSI. This is the generalized degeneracy considered in [11] which occurs due to the  $\epsilon_{ee}$  parameter. A special case is  $\epsilon_{ee} = -1$  for which, as mentioned in the introduction, the NSI effect cancels the usual matter effect. In the absence of the off-diagonal NSI parameters, the probability expression for NH assumes the form in vacuum<sup>2</sup>:

$$P_{\mu e} = x^2 \sin^2 \Delta + y^2 + 2xyg \sin \Delta \cos(\delta_{CP} + \Delta). \quad (6)$$

This has a  $\Delta \rightarrow -\Delta$  and  $\delta_{CP} \rightarrow \pi - \delta_{CP}$  degeneracy. If  $\delta_{CP}$  is measured accurately such that  $\pi - \delta_{CP}$  is not allowed then this degeneracy can be alleviated. However for true value of  $\delta_{CP} = \pm\pi/2$  since both  $\delta_{CP}$  and  $\pi - \delta_{CP}$  are same there is an intrinsic degeneracy which cannot be removed even if  $\delta_{CP}$  is measured precisely around these values. Note that for  $\delta_{CP} = \pm\pi/2$ ,  $\cos(\delta_{CP} + \Delta) \rightarrow \sin \Delta$  and hence the third term becomes  $\sin^2 \Delta$  and there is no hierarchy sensitivity even for a fixed  $\delta_{CP}$ . It's also noteworthy that this degeneracy will be there for all baselines and hence no LBL experiment will be able to resolve this degeneracy.

We also note that since the nature of the octant degeneracy as a function of  $\epsilon_{ee}$  is different for neutrinos and antineutrinos running in ( $\nu + \bar{\nu}$ ) mode will take care of the wrong octant solutions. Thus in this paper we do not consider the wrong octant solutions. In which case, these probability figures also show that when  $\epsilon_{ee} > 2$  there will not be any hierarchy degeneracy.

So far we discussed hierarchy degeneracy for  $\delta_{CP} = -\pi/2$ . In fig. (2) we have plotted the probability vs  $\delta_{CP}$  for various values of  $\epsilon_{ee}$  to understand the degeneracies due to  $\delta_{CP}$  in presence of NSI. The bands are over  $\theta_{23}$  in LO ( $39^\circ - 42^\circ$ ).

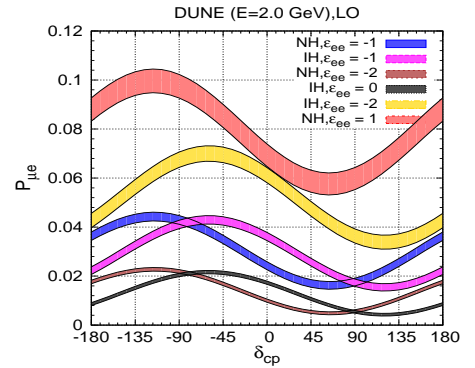


FIG. 2:  $P_{\mu e}$  vs  $\delta_{CP}$  for DUNE by considering fixed energy ( $E=2$  GeV) for various values of  $\epsilon_{ee}$ . Here, the bands are for  $\theta_{23}$  only for LO.

The various degenerate solutions observed are,

<sup>2</sup> At  $\epsilon_{ee} = -1$ ,  $f = \sin \Delta (-\sin \Delta)$  and  $g = 1(-1)$  for NH (IH).

- The WH-RO- $R\delta_{CP}$ <sup>3</sup> solution, discussed above, occurs at  $\delta_{CP} = \pm\pi/2$ . This is seen by comparing the blue and magenta bands or the brown and the grey bands. Mathematically the above implies  $P_{\mu e}^{NH}(\epsilon_{ee}, \delta_{CP} = \pm\pi/2) = P_{\mu e}^{IH}(-\epsilon_{ee} - 2, \delta_{CP} = \pm\pi/2)$ . This degeneracy will be there even if  $\delta_{CP}$  is measured precisely around the maximal value. However a precise measurement of  $\epsilon_{ee}$  can help to remove this degeneracy apart from  $\epsilon_{ee} = -1$ .
- We also have WH-RO-W $\delta_{CP}$  solutions which can be observed by comparing the blue band with magenta band or brown band with grey band by drawing a horizontal line corresponding to a given probability. This can be defined as  $P(\epsilon_{ee}, \delta_{CP}) = P(-\epsilon_{ee} - 2, \delta'_{CP})$ .
- Apart from the degenerate solutions corresponding to  $\epsilon_{ee} \rightarrow -\epsilon_{ee} - 2$  one can have a more general form of the degeneracy  $P(\epsilon_{ee}, \delta_{CP}) = P(\epsilon'_{ee}, \delta'_{CP})$ . This can be seen by comparing the yellow band with the dark-red band. The conclusions made above are also true for antineutrinos.

**Off-diagonal NSI :** We study the cases of whether inclusion of off-diagonal NSI parameter  $\epsilon_{e\tau}$  can resolve the intrinsic hierarchy degeneracy occurring at  $\epsilon_{ee} = -1$  and  $\delta_{CP} = -\pi/2$ .<sup>4</sup> From eq.(4) (valid for small magnitudes of  $\epsilon_{e\tau}$ ) the difference in hierarchy for  $\epsilon_{ee} = -1$  and  $\delta_{CP} = -\pi/2$  and same  $\epsilon_{e\tau}$  in both NH and IH can be expressed as,

$$P_{\mu e}^{NH} - P_{\mu e}^{IH} = 8\hat{A} \sin \Delta c_{23} s_{23} (x \sin \Delta - x \cos \Delta + y \sin \Delta) \epsilon_{e\tau} \sin \phi_{e\tau} \quad (7)$$

Here, we used  $f = \pm \sin \Delta$ ,  $g = \pm 1$  for  $\epsilon_{ee} = -1$  and  $\pm$  sign is for NH(IH). Thus, we can see that there is a finite difference between the NH and IH probabilities and this will vanish if  $\phi_{e\tau}$  is zero or if  $\phi_{e\tau} \rightarrow -\phi_{e\tau}$ . However, the intrinsic degeneracy, although not there for  $\epsilon_{ee} = -1$  may shift by an amount which depends on the values of the off-diagonal NSI parameters. For instance, assuming a small shift 'q' in presence of  $\epsilon_{e\tau}$  one can write  $P^{NH}(\epsilon_{ee} + q, \epsilon_{e\tau}, \delta_{CP} = \pm\pi/2) = P^{IH}(\epsilon_{ee} + q, \epsilon_{e\tau}, \delta_{CP} = \pm\pi/2)$  then assuming  $\delta = -\pi/2$  and  $\theta_{23} = \pi/4$ , q can be calculated at the oscillation maxima ( $\sin \Delta \sim \pi/2$ ) as,

$$q = -\frac{0.23 \sin \phi_{e\tau} \epsilon_{e\tau}}{0.046 - 0.03 \cos \phi_{e\tau} + 0.01 \epsilon_{e\tau}^2} \quad (8)$$

For instance, for  $\epsilon_{e\tau} = 0.05(0.5)$  and  $\phi_{e\tau} = -90^\circ$ , eq.(8) gives  $q \simeq 0.25(2.37)$ . This shift can be observed from the green(blue) dashed and solid lines of fig. (3). These two cases demonstrate degeneracy of the form

$P^{NH}(\epsilon_{ee}, \delta_{CP}, \epsilon_{e\tau}, \phi_{e\tau}) = P^{IH}(\epsilon_{ee}, \delta_{CP}, \epsilon_{e\tau}, \phi_{e\tau})$  with  $\epsilon_{ee} \neq -1$  and  $\delta_{CP} = \pm\pi/2$ .

Additionally, we can also observe more general degeneracy of the form  $P^{NH}(\epsilon_{ee}, \delta_{CP}, \epsilon_{e\tau}, \phi_{e\tau}) = P^{IH}(\epsilon'_{ee}, \delta_{CP}, \epsilon'_{e\tau}, \phi_{e\tau})$  by drawing horizontal lines intersecting the green(blue)-dashed and blue(green)-solid lines. Figure (3) is drawn for fixed values of  $\delta_{CP}$  and  $\epsilon_{e\tau}$ . Allowing these parameters to vary can generate additional degeneracies. Note that eq.(8) and fig.(3) correspond to the energy at which the oscillation maxima occurs. We have verified that for a different energy the point of intrinsic degeneracy occurs at a different value. Thus the inclusion of the energy spectrum information can reduce the impact of this degeneracy in presence of off-diagonal NSI parameters.

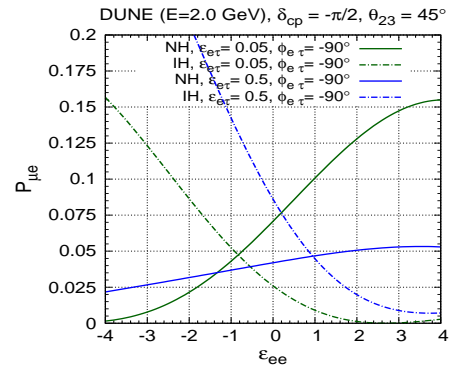


FIG. 3:  $P_{\mu e}$  vs  $\epsilon_{ee}$  for different  $\epsilon_{e\tau}$  values in the case of DUNE.

In fig. (4) we plot hierarchy  $\chi^2$  vs  $\epsilon_{ee}$  (Test) to understand how the diagonal and off-diagonal NSI effect the mass hierarchy sensitivity of DUNE while assuming NSI in nature. We have used General Long baseline Experiment Simulator (GLoBES) [21, 22] with additional tools from [23, 24] in our numerical calculations. The experimental specifications and other numerical details are taken from [25] except that this analysis is done for 40 kt detector mass. The true values that we have considered are,  $\sin^2 \theta_{12} = 0.297$ ,  $\sin^2 2\theta_{13} = 0.085$ ,  $\theta_{23} = 45^\circ$ ,  $\delta_{CP} = -\pi/2$ ,  $\Delta m_{21}^2 = 7.37 \times 10^{-5} \text{eV}^2$  and  $\Delta m_{31}^2 = 2.50 \times 10^{-3} \text{eV}^2$  which are consistent with the global fit to neutrino oscillation data [1, 2]. Different true values of NSI parameters are as mentioned in the fig. 4. We marginalize over  $\theta_{13}$ ,  $\delta_{CP}$ ,  $\epsilon_{e\tau}$  and  $\phi_{e\tau}$ . The remaining NSI parameters are taken to be zero. The bounds on NSI parameters [16, 26, 27] that occur in  $P_{\mu e}$ , eq.(4), at 90% C.L. are considered to be  $|\epsilon_{ee}| = 4$ , and  $\epsilon_{e\tau} < 3.0$  and the corresponding off-diagonal phase  $\phi_{e\tau} = [-\pi, \pi]$ .

The black solid curve shows that there is no hierarchy sensitivity for  $\epsilon_{ee} = -1$  in the absence of other NSI parameters because of the intrinsic degeneracy in the appearance channel. Here, the small non-zero  $\chi^2$  at  $\epsilon_{ee} = -1$  is arising from the disappearance channel  $P_{\mu\mu}$  of the experiment.

<sup>3</sup> Note that WH = Wrong Hierarchy, RO = Right Octant,  $R\delta_{CP}$  = Right  $\delta_{CP}$ ,  $W\delta_{CP}$  = Wrong  $\delta_{CP}$ .

<sup>4</sup> Since, the bounds on  $\epsilon_{e\mu}$  are more tightly constrained than  $\epsilon_{e\tau}$  we consider the effect of latter.



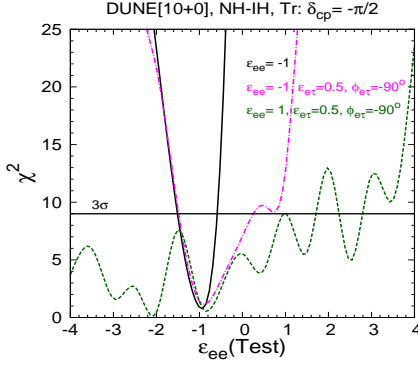


FIG. 4: Hierarchy  $\chi^2$  for DUNE vs  $\epsilon_{ee}$  (Test) considering known octant ( $\theta_{23} = 45^\circ$ ). The black curve corresponds to the presence of only  $\epsilon_{ee}$ . True values of NSI parameters are displayed.

The magenta curve shows the hierarchy sensitivity for a non-zero true value of  $\epsilon_{e\tau} = 0.5$  and  $\phi_{e\tau} = -\pi/2$ . We find that for this the global minima comes at  $\epsilon_{ee} = -0.8$  and there is no hierarchy sensitivity.

Note that there is also a local minima for  $\epsilon_{ee} = 1$ , where we observed an intrinsic degeneracy in fig. 3. The reason that we do not get the global minima at this value is due to (i) marginalization over the phase  $\phi_{e\tau}$ , which had been kept fixed in fig. 3, (ii) the broadband nature of the beam at DUNE. The green dotted curve depicts the hierarchy sensitivity for a different true value of  $\epsilon_{ee} = 1$ . For this case the global minima comes at  $\epsilon_{ee} = -2$  as well as a very close minima near  $\epsilon_{ee} = -1$  and several other local minima. The global minima in this figure exhibits the most general form of the degeneracy:  $P^{NH}(\epsilon_{ee}, \delta_{CP}, \epsilon_{e\tau}, \phi_{e\tau}) = P^{IH}(\epsilon'_{ee}, \delta'_{CP}, \epsilon'_{e\tau}, \phi'_{e\tau})$ . These figures indicate that in presence of true non-zero NSI parameters DUNE will not have any hierarchy sensitivity if marginalized over the model independent ranges of NSI parameters. Alternatively, if hierarchy sensitivity is observed in DUNE then certain ranges of NSI parameters will be ruled out. For instance assuming presence of only one diagonal NSI parameter the range  $-1.6 < \epsilon_{ee} < -0.8$  will be ruled out if DUNE observes  $3\sigma$  hierarchy sensitivity. Similarly, with the inclusion of  $\epsilon_{e\tau}$ ,  $(2-3)\sigma$  sensitivity can be achieved by DUNE if certain ranges of  $\epsilon_{ee}$  are disfavoured. For instance from the magenta curve if  $0.25 < \epsilon_{ee}$ , a  $3\sigma$  sensitivity can be achieved. For the green curve this range is  $0.8 < \epsilon_{ee}$  for a  $2\sigma$  hierarchy

sensitivity.

In this work we have considered the model independent bounds on the NSI parameters. If however, we use the more restrictive model dependent bounds then the hierarchy sensitivity of DUNE can improve considerably. For instance assuming only diagonal NSI and the model dependent bound  $-0.9 < \epsilon_{ee} < 0.75$  [16, 27],  $3\sigma$  hierarchy sensitivity can be achieved for  $-0.7 < \epsilon_{ee}$  and it can be very large for higher values of  $\epsilon_{ee}$  [13].

**Conclusions :** The DUNE experiment has very good hierarchy sensitivity within the standard oscillation scenario. However if expected results are not obtained it could be a signature of non-standard neutrino interactions. We observe that if  $\delta_{CP} = \pm\pi/2$  then the generalized hierarchy degeneracy  $\epsilon_{ee} \rightarrow -\epsilon_{ee} - 2$ ,  $\delta_{CP} \rightarrow \pi - \delta_{CP}$  [11] becomes an intrinsic  $\delta_{CP}$  degeneracy which cannot be removed even if  $\delta_{CP}$  is measured very precisely. This result assumes more importance in the light of the preference of current data for  $\delta_{CP} \sim -\pi/2$ . In addition if the diagonal NSI parameter  $\epsilon_{ee} = -1$ , the standard matter effect gets compensated by the NSI effects and in absence of any off-diagonal NSI parameters one gets an exact intrinsic hierarchy degeneracy which cannot be removed even if both  $\epsilon_{ee}$  and  $\delta_{CP}$  are known precisely. Moreover, this is independent of baseline and energy and hence cannot be resolved by the LBL experiments like T2K, NO $\nu$ A and DUNE. When the off-diagonal NSI parameter  $\epsilon_{e\tau}$  is included the intrinsic hierarchy degeneracy is transported from  $\epsilon_{ee} = -1$  to a different value depending on the off-diagonal NSI parameters as well as energy. Moreover the uncertainty in the magnitude and phase of the off-diagonal NSI parameters can give rise to additional degeneracies when one marginalizes over the full range. Due to all these degeneracies the hierarchy sensitivity of DUNE gets seriously compromised. A  $(2-3)\sigma$  hierarchy sensitivity can be obtained in presence of non-zero  $\epsilon_{e\tau}$ , if  $\epsilon_{ee}$  is known more precisely. Thus if DUNE observes hierarchy sensitivity then constraints can be obtained on the allowed ranges of NSI parameters which will exclude the degenerate regions corresponding to the true values of the NSI parameters. Measurement of these parameters from non-oscillation experiments [28–30] can further help in addressing these degeneracies.

**Acknowledgement:** The authors thank Monojit Ghosh for his help with the code and many useful discussions.

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